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THESIS

LOCOMOTION IN VIRTUAL ENVIRONMENTS AND
ANALYSIS OF A NEW VIRTUAL WALKING DEVICE

by

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March 2005

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13. ABSTRACT (maximum 200 words)

   This thesis investigates user interfaces for locomotion in virtual environments (VEs). It looks initially at virtual environments and user interfaces, then concentrates on locomotion interfaces, specifically on the Omni-Directional Treadmill (ODT) (Darken and Cockayne, 1997) and a new virtual walking device, LocoX, which was developed at the MOVES Institute, Naval Postgraduate School. It analyzes and compares the ODT and LocoX in terms of the application of human ability requirements (HARs). Afterwards, it compares the results of the analysis of the ODT and LocoX to real-world locomotion.

   The analysis indicates that LocoX, a new way of exploring virtual environments (VEs), provides a close match to real locomotion on some subtasks in VEs--compared to the ODT--and produces relatively closer representation on some subtasks of real world locomotion. This thesis concludes that LocoX has great potential and that the locomotion provided is realistic enough to simulate certain kinds of movements inherent to real-world locomotion. LocoX still requires maturation and development, but is nonetheless a viable locomotion technique for VEs and future game-based simulations.

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VIRTUAL WALKING DEVICE

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ABSTRACT

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I.   INTRODUCTION

A.   PROBLEM STATEMENT

The question that this thesis attempts to answer is whether it is possible to provide robust locomotion in virtual environments (VEs) by using a new, cost-effective algorithm.

Locomotion is something that people have studied for years. All of the efforts were basically aimed at providing better locomotion in VEs due to the importance of simulating environments and making people feel as if they are in the real world even though they are not.

This thesis will not go into detail about the new algorithm mentioned above, but will compare it to other known locomotion devices, such as Omni-Directional Treadmill (ODT).

The next step will be comparing the results of the analysis of the two locomotion devices to real-world locomotion and answering the question of whether the algorithm is good enough to be used as a robust locomotion device in VEs.

Finally, this thesis will discuss how to set up a detailed, measured and statistically analyzed experiment of locomotion in the real world, both on the ODT and with the new virtual walking device. Then it will try to answer what would be expected for results from such an experiment.

The algorithm mentioned in this thesis is developed and well explained in another Master's Thesis, "An Algorithm for a Cost Effective, Small Footprint Locomotion

Device", by Alex Mabini (2004) and can be found in the List of References. Detailed information about this thesis can also be found in Appendix-B.

B.   MOTIVATION

Locomotion has always been one of the main concerns in the field of Virtual Environments. It has been studied for years. Researchers have tried to improve locomotion in VEs, and have designed and explored new devices such as the ODT.

When you think of a virtual environment, what do you think about as the main components? You think of a computer with the basic components such as keyboard, mouse, and screen, and maybe some extra gadgets to support the VE, such as a Head-Mounted Display (HMD), etc. Even though the motion (i.e., walking, running) can be provided in the VE with the movement of the mouse or with some key presses, how realistic would it be? Would it not be much closer to real-world locomotion if some kind of environment could be provided so that the person who was exploring the VE could move his legs and feet as he would in the real world, yet not physically travel a far distance (i.e., walk-in-place)?

How to make feel people as if they are in the real world? How to force people to feel more immersed in the virtual environment? What would be the main elements to make people behave as they would in real environments? Would simulating "walking" by dragging the mouse or pressing a key (i.e., up arrow key), or providing "running" by pressing an extra key at the same time, make you feel as if you are actually walking or running?

These questions lead to the discussion about locomotion in VEs, and that will be the main concern of this thesis.

C.   THESIS ORGANIZATION

Four chapters comprise this research:

Chapter I – Introduction: Identifies the purpose and motivation behind conducting this research.

Chapter II – Background and Previous Research: Briefly describes the locomotion and provides information on virtual environments, user interfaces used in VEs, and previous research about locomotion interfaces.

Chapter III – Task Analysis of LocoX: Analyzes the Omni-Directional Treadmill (ODT) and LocoX in terms of HARs and compares the results to real-world locomotion.

Chapter IV – Conclusions and Future Work: Explains the conclusions and gives recommendations about possible future work.

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II. BACKGROUND AND PREVIOUS RESEARCH

A.   OVERVIEW

This section covers the general areas of interest for this thesis, which are locomotion and virtual environments.

1.   What is Locomotion?

Locomotion is defined as "the act of moving, or the ability to move, from place to place" in the glossary of Neurolab of NASA (Havelka and Heath, 1998). Another definition in the Merriam-Webster on-line dictionary is "an act or the power of moving from place to place."

Even though the above dictionary definitions of locomotion are satisfactory enough for general purposes, locomotion, with the meaning that will be used in VE terminology, is a bit different. As Darken and Cockayne (1997) define in their research paper for locomotion on the Omni-Directional Treadmill (ODT), whenever you need to map a physical space to a larger virtual space in a virtual environment, you should provide a special mechanism for users to move over large distances in the virtual world that you create, without actually moving far in the real, physical space within the experiment area. Then they state in their research:

> We refer to this mechanism as locomotion, as opposed to navigation which implies not only the motor elements associated with movement but also the cognitive elements of wayfinding. (Darken and Cockayne, 1997).

Thus, the terms navigation and locomotion are distinctly separated, which makes sense from the perspective of cognitive movement. If you are navigating, you need to use some sort of cognitive element so that you

can get help finding your way in the virtual world. Depending on the experiment to which you are being exposed, and based on the assumption that you have some goals or tasks to accomplish, you cannot just wander in the VE without trying to use some cognitive skills. Hence, locomotion must be differentiated from navigation as a mechanism that is directly related to a physical movement (i.e., walking in place, pushing a joystick etc.).

2.   Why is Locomotion Needed in VEs?

Virtual environments and 3D worlds are being used in a wide range of applications, and for a variety of different tasks. Immersion, which is defined as the feeling of "being there" (substituting the physical environment with VE), becomes one of the most important factors of a VE, especially for applications such as training and simulation. If the user can be immersed such that he can interact with the environment by using his natural behavior, then he can easily learn about this new world with which he was not previously familiar. After passing these "immersion" and "recognition" steps, the user can have great knowledge about the running of the whole system and simulation by building some mental models himself.

Today, some of the VE applications (e.g., training, entertainment, etc.) need basic skills and others need advanced, complex skills (e.g., art, robotics, scientific applications, etc.) The interest of this thesis is especially in applications that require full immersion by VE, such that the VE becomes no different from the real world for the user. Most of these kinds of VEs do not need

complex skills (e.g., military training), but rather the movement of the whole body, either with or without gross body coordination.

How can one think of such a VE, for instance a virtual environment for a military training or simulation, without locomotion? How realistic would that simulation or training be without providing some sort of mechanism that makes the user actually move his legs and feet in the physical space? Obviously, in such a VE, one cannot expect a soldier to get the maximum amount of training from the virtual environment if the way that he moves his body is provided by pressing some keys or moving the mouse in a 2D desktop environment. How can the sensations of both actual and imagined running be made to be the same?

B.   RELATED RESEARCH & BACKGROUND

1.   Virtual Environments (VEs)

How to define virtual environments? What would be a good definition an environment must meet in order to be called virtual? Any three-dimensional computerized world? Is it possible that a book or maybe the computer on your desk may be a VE? Maybe a movie that you see with special 3D glasses at a movie theater?

In general, a virtual environment can be defined simply as "a computer-generated, 3D spatial environment in which users can participate in real time." However, this definition leaves out many other environments that are not computer generated, such as books and movies. Moreover, if "immersion" is specified as one of the main characteristics of VEs, then how to express that a person who does not hear

what you say when he is reading a book is not in a virtual environment? Is he not immersed? Is not the world that he is living in at that moment virtual?

These and similar questions occupied researchers' minds for several years. Nowadays, there are so many environments that can be called virtual (e.g., computer applications for training, entertainment, flight simulators, etc.) that any single definition is not good enough to give an exact definition of a virtual environment. However, there are some common concepts which should be satisfied in order for that environment to be called a virtual environment, although it is not possible to give a generic, "one size fits all" definition of VEs.

Figure 1.   An example of computer-generated virtual environment

A virtual environment can be fully immersive or non-immersive (i.e., "through the window" worlds). To some extent it replaces the real-world stimuli by synthetic

computer-generated stimuli. However, these and some other concepts (i.e., perception, sensation, reality, etc.) are not going to be investigated here in detail since they are beyond the scope of this research. However, this thesis will take a short look at common user interfaces that are used for VEs in general.

2.   User Interfaces for Virtual Environments (VEs)

Interaction is one of the main concepts of VEs. Without it, any VE would be almost static. Because the whole purpose of VEs is to simulate any environment, task, duty, training, or situation, a goal of this work will be to look for some kind of interaction between the virtual world and the user, so that the user can participate in real time.

On the other hand, the user will need cues, just as he would need in the real world, so that he can be familiar with the virtual world and interact with it. The input or information for the user can be provided in different ways.

- <u>Visual Sense:</u> is the most important/efficient way to give strong cues to the user (almost 70% of all sensory input), so much so that even a quick glance at the screen will be enough to process most of the details of the scene. Visual input is definitely a necessary requirement to make the user engage with the VE. The visual sense can be provided with:

  - 2D flat desktop screen (either LCD or CRT display),

  - CAVE (The CAVE is an immersive, projection-based, virtual reality system developed at the Electronic Visualization Lab (EVL)),
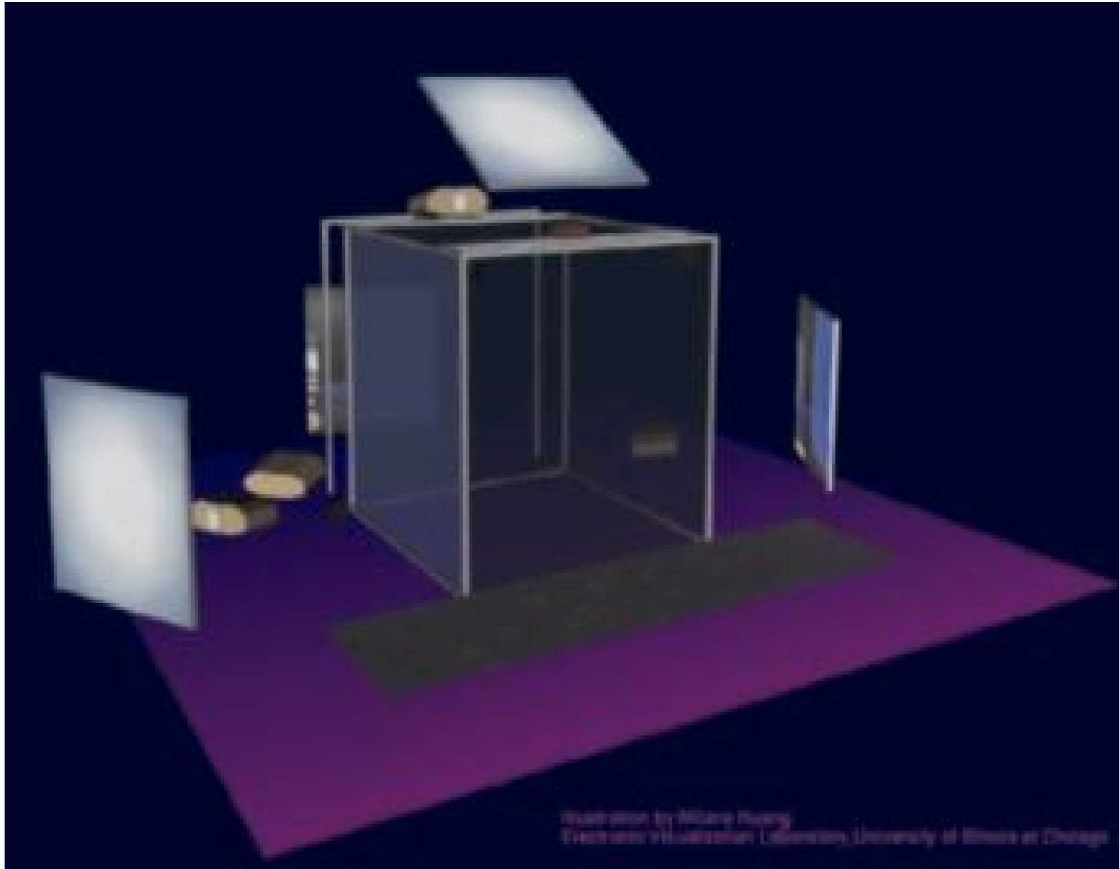
Figure 2.   General CAVE structure. Photo courtesy of Dave's
CAVE Page, EVL, University of Illinois at Chicago
(UIC))

- Head-mounted display (HMD) (projected HMD,
  mini HMD).

Figure 3.   Mini Head-mounted display (HMD). Photo courtesy
of Cybermind NL, Hi-Res900-3D model

- Various   configurations   of   projection
  displays (usually big screen).

- Aural sense: is the second important factor in familiarization with VE, with an efficiency percentage of approximately 20%. Auditory localization cues help locate the position in space of a sound source. There are eight sources of localization cues: interaural time difference, head shadow, pinna response, shoulder echo, head motion, early echo response, reverberation, and vision. The first four cues are considered static and the others dynamic. Dynamic cues involve movement of the subject's body, affecting how sound enters and reacts with the ear. (Foster, 1991). These eight localization cues are explained by Burgess (1992). There is also another field of research in this area that deserves note: 3D sound (also known as "spatial sound"). In fact, this is the sound that you hear in everyday life. Sounds from various sources come to the ear from all directions and distances, and are distinguished by their characteristics. This helps to locate the objects from a three-dimensional aspect. The interfaces for aural sense may be:

  - Stereo headphones,

  - Built-in speakers in a HMD,

  - Conventional speaker systems,

  - Surround sound systems for 3D sound (spatial sound).

- Olfactory Sense: is one of the rarely used (approx. 5%) cues in VEs since it is quite hard to simulate smell. However, if some olfactory information can be given to the user, it is a fact that it will enhance the user's sensation and recognition.

- Gustatory Sense: is another less important cue (approx. 4%) to consider in VEs, due to the difficulty of simulation. There are also very few simulations that require user taste to gain information about the VE.

- Tactile Sense: it is highly important to get some information about the objects in real life, but unfortunately researchers are still trying to figure out a way to simulate the sense of "touch"

in VE. Even though there have been some serious studies of haptic technology in the past (i.e., gloves with several tiny sensors on it to reflect the state of fingers etc.), for now, tactile sense takes its place as the last in the list of senses, with an approximate percentage of 1%.

With improvement in technology over the years, there are now many different options to provide information to the user, with a wide variety of user-interfaces, as seen above. However, some things that complete the experience of the user in virtual reality, such as movement of the body (i.e., arms and legs), are still missing. This is the point where locomotion becomes important in VEs. However, in order to get the maximum benefit from it, there must be some sort of interface to provide efficient, robust communication/interaction for the mechanism of locomotion.

3. Locomotion Interfaces for Virtual Environments (VEs)

a. *Overview*

This section will address locomotion interfaces for VEs. Motion interfaces are used when traveling through a virtual environment (VE), and are characterized by Durlach and Mavor (1995) as either active or passive. Locomotion interfaces fall under the active category, since the user needs some significant energy exertion while he does not need it with passive motion interfaces. The passive interfaces are grouped into two sub-categories, inertial and non-inertial.

```
                    ┌─────────────┐
                    │   Motion    │
                    │  Interfaces │
                    └─────────────┘
                           │
          ┌────────────────┴────────────────┐
   ┌─────────────┐                    ┌─────────────┐
   │   Active    │                    │   Passive   │
   │  Interfaces │                    │  Interfaces │
   └─────────────┘                    └─────────────┘
          │                           ┌──────┴──────┐
   ┌─────────────┐            ┌─────────────┐ ┌──────────────┐
   │ Locomotion  │            │  Inertial   │ │ Non-inertial │
   │ Interfaces  │            │ Interfaces  │ │  Interfaces  │
   └─────────────┘            └─────────────┘ └──────────────┘
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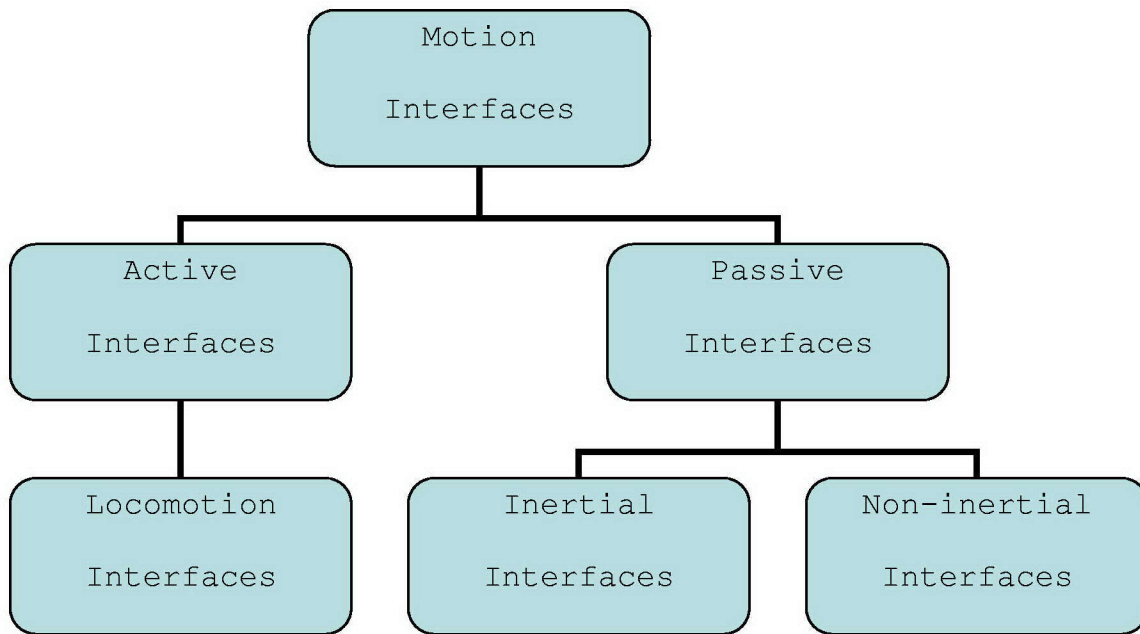
The main difference between active and passive motion interfaces, which also separates locomotion interfaces from all others, is repetitive limb motion or *gait*. In locomotion interfaces, users move their arms and legs such that they expend energy by repetitive limb motion. Energy expenditure in gait and position control, with repeated cycling of the device to cover the VE workspace, is the key features of locomotion (active) interfaces. (Hollerbach, 2002)

In passive locomotion interfaces, the user does not usually move his body or expend energy. He either manipulates some control mechanism or makes small moves to change his position in VE. A person in a flight simulator is an example of an inertial interface (making small moves but not necessarily expending much energy); while a user who is operating a trackball or joystick is an example of a non-inertial passive interface (manipulating a control mechanism without moving his body). Hollerbach (2002)

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states that the rate control becomes the key feature of passive motion interfaces since repetitive motions are not required by the user to move through a virtual environment.

b. Locomotion Interfaces

Locomotion interfaces are energy-extractive interfaces to virtual environments. They simulate unrestrained human mobility, in limited space, for large-scale virtual environments and provide a way to overcome the limitations of joystick maneuvering, whole-body motion platforms (e.g., the user is seated and does not expend energy), and room environments, where only short distances can be traversed. (Christensen, Hollerbach, Xu, and Meek, 2000).

Throughout the years, there have been numerous approaches for the design of locomotion interfaces, such as powered pedaling devices (Brogan, Metoyer, and Hodgins, 1998), programmable foot platforms (Iwata, 2000), walking-in-place studies (Templeman, Denbrook, and Sibert, 1999), and treadmill-style devices.

(1) <u>Pedaling devices</u> are mostly derived from the exercise machines that you can find in any gym today (e.g., stationary bicycles). Sensors on pedals and handlebars provide the information for linear motion and direction; handlebars are also used for turning purposes. If slope simulation is required, then a motor is needed to tilt the device.

Brogan, Metoyer and Hodgins (1998) employed a pedaling device (racing bicycle simulator) study with a platform capable of tilting +/- 12 degree to simulate hills (Figure 4.a and Figure 4.b).

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By using this locomotion interface, they achieved physically correct reactions to the environment and, to some extent, a satisfactory degree of realism for the users.

a. Pedaling device   b. Computer model

Figure 4.   Pedaling device examples. Photos courtesy of Brogan, Metoyer and Hodgins, College of Computing, Georgia Institute of Technology.

Another example of a pedaling device is the SARCOS Uniport, built on a turntable (see figure below). Turning is achieved by the load sensors that measure the force applied by the user to the seat.
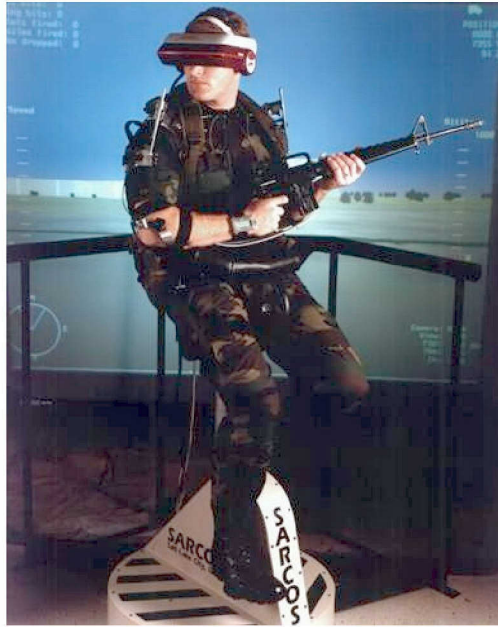
Figure 5.   SARCOS Uniport

(2) Programmable foot platforms are also derived from exercise machines, (e.g., stair-stepper). Iwata's GaitMaster (Iwata and Yoshida, 1999) is a significant example of this category. In the first version of his study (Figure.6.a) there is no turning capability, but forward and backward motion is available. In the later version (Figure 6.b), two 3-degree-of-freedom (DOF) platforms are mounted on a turntable to provide turning.

a. Straight Forward Type   b. Omni-directional Type
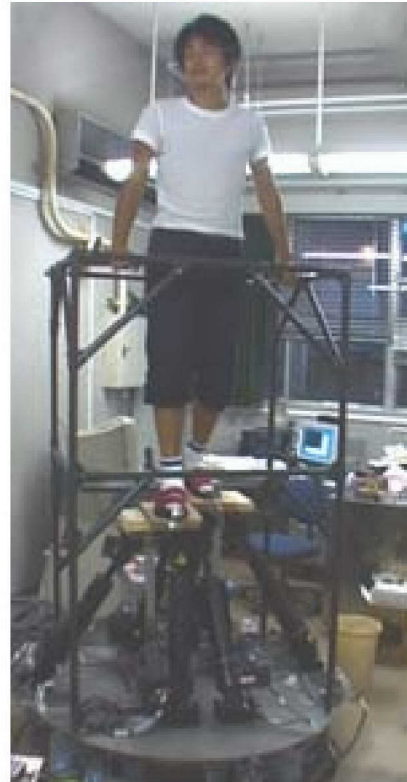
Figure 6.   GaitMaster. Photos courtesy of Virtual Reality Lab, University of Tsukuba

(3) Walking-in-place is another option for locomotion interfaces. Templeman, Denbrook, and Sibert (1999) conducted the first major study in this field. They followed motions of the user with the help of magnetic trackers attached to the thighs and force sensors in the footpads (see the figures below). There were also magnetic trackers placed at the waist and head, and a handgrip. The position and orientation are controlled by the waist sensor. The Head-Mounted display (HMD) and head sensor are used for determining the gaze direction.
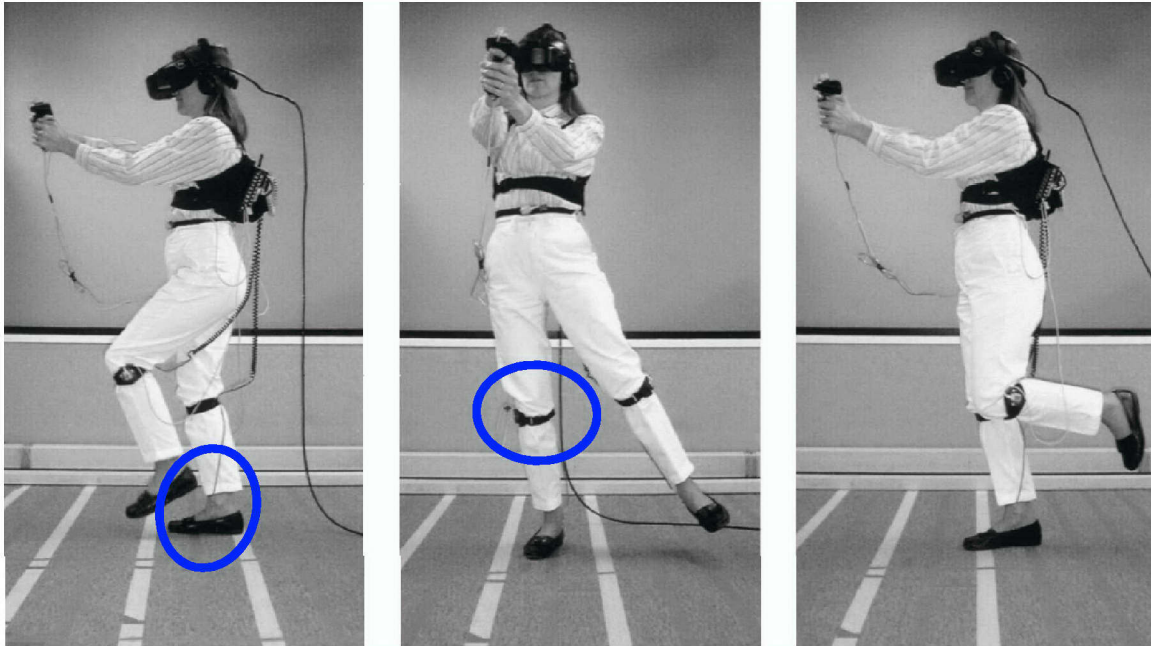
Figure 7.   The Gaiter System. Photo courtesy of Templeman, J.N.

        Even though the user is not really showing physical motion for forward/backward walking, rocking the knees is enough to indicate the movement direction in this design. Turning is also available by swinging the appropriate knee to the side while walking forward.

        Mabini (2004) reported a new locomotion device for virtual environments, called LocoX. He has developed an algorithm to figure out the user's movement by evaluating the information that he got from the three magnetic sensors (trackers) attached to the user's body. He used one sensor for each leg (on the knees) to recognize the state of the legs (e.g., walking, running, sidestepping, etc.) and a third sensor attached to the top of the Head-Mounted Display (HMD) to figure out the direction in which the user is looking.
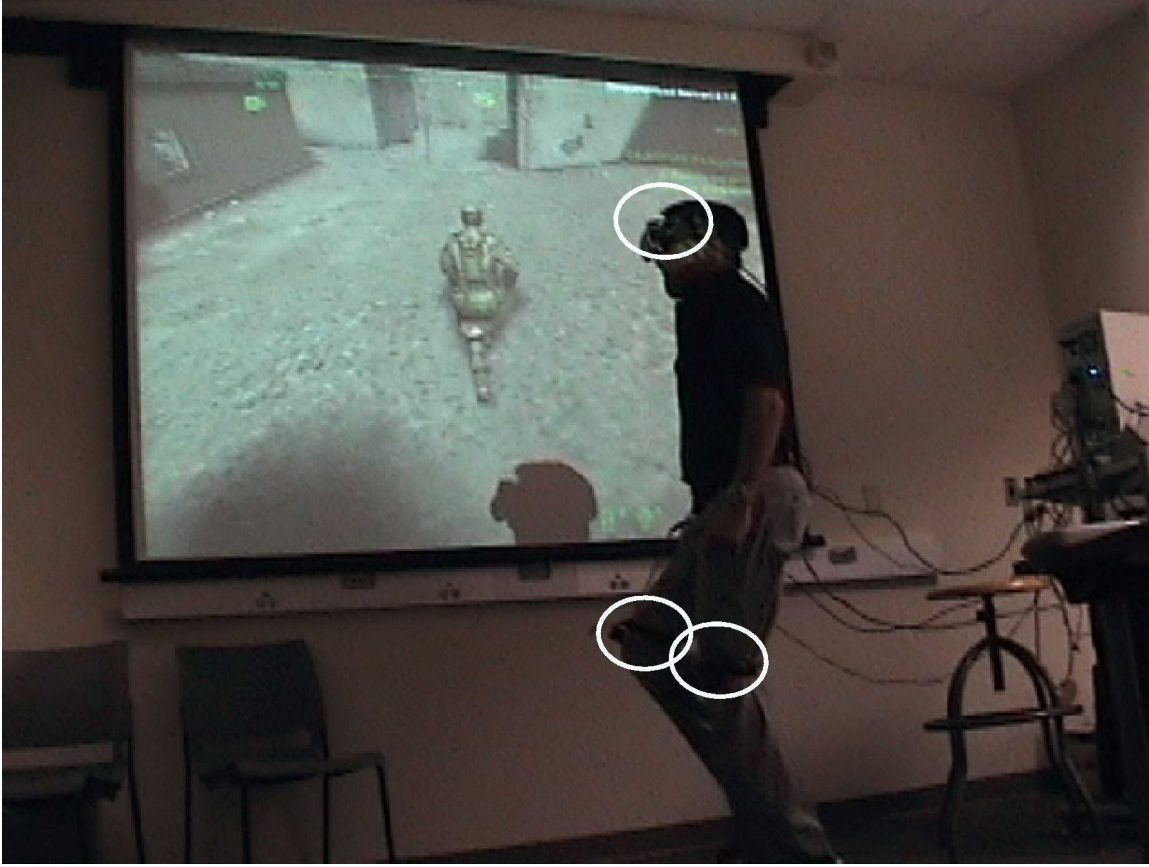
Figure 8.   LocoX: Virtual Walking Device Photo courtesy of
Mabini, A. MOVES Institute, Monterey, CA.

Although the same muscular forces are not
used to provide forward/backward movements as in the other
locomotion interfaces, these walk-in-place interfaces have
the great advantage of being potentially lower-cost systems
(i.e., no motion platform, etc.)

(4) <u>Treadmill-style devices</u> are the ones
that seem to be the most attractive alternative to walking
and running because of the relatively natural feeling they
give to the user.

There have been various studies with
different designs of treadmills. A passive/non-motorized
treadmill and instrumented bicycle handlebars for steering

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were studied by Brooks, et al (1992). Another passive treadmill was studied by Witmer and Kline (1998). Noma and Miyasato (1998) studied the ATLAS system, which uses an active treadmill on a spherical joint, which can act as a turntable but is also capable of tilting upward and sideways.

Figure 9.   The new SARCOS Treadport. Photo courtesy of Hollerbach, J.M.

The Sarcos Treadport is comprised of a large tilting treadmill, an active mechanical tether attached to the user through a body harness to measure body movement and apply forces to the user for various purposes, and a CAVE-like visual display (Hollerbach, Christensen, Xu, and Jacobsen, 1999).

Darken and Cockayne (1997) evaluated the Omni-Directional Treadmill (ODT) designed and built by Virtual Space Devices, Inc. ODT is a two-dimensional active treadmill that works with two orthogonal roller belts. A

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mechanical tracking arm on an overhead boom measures body
position and applies bias forces to center the user.

Figure 10.   Omni-directional Treadmill (ODT) Photo courtesy
        of Darken, R. Naval Postgraduate School, Monterey, CA.

        Of all the locomotion devices listed above,
this thesis will study and analyze the new walking (walk-
in-place) device, LocoX, and the Omni-Directional Treadmill
(ODT), compare them to real-world locomotion, and try to
answer the following questions:

- How does LocoX compare to the ODT?

- To what extent can LocoX provide a good
  representation of real-world locomotion?

- Is LocoX a robust locomotion device?

- How would one design an efficient experiment with
  LocoX?

- What is in the future for LocoX?

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III. TASK ANALYSIS AND COMPARISON OF VE LOCOMOTION IN REAL WORLD, ODT AND LOCOX

A. INTRODUCTION TO ANALYSIS

This section will compare LocoX to ODT and real-world locomotion in terms of a well-developed taxonomy (classification methodology), Human Ability Requirements (HARs) (see Appendix-B for a detailed explanation of HARs used in this research).

This taxonomy has been used in various studies (e.g., Wilson, Barnard, Green, &MacLean, 1988; and Rose, Fingerman, Wheaton, Eisner, & Kramer, 1974). It was initially intended to classify human capabilities required for different classes of work. The resulting and codified study has been published as the Fleishman-Job Analysis Survey (F-JAS; Fleishman, 1995) and more recently by the Department of Labor as O*NET.

An example of HARs is given below as it is described in the F-JAS; *Gross Body Coordination*. It is defined as "the ability to coordinate the movement of the arms, legs, and torso together in activities where the whole body is in motion."

All of the human abilities defined in F-JAS have a representative name and definition. This definition allows the analysis of human task components using an *absence/presence* evaluation. Absence/presence evaluation is basically the use of a standard definition to decide whether the idea or task component presented in the definition is absent or present in the system that is being studied. A list of task components used in this study is given in Appendix-A.

Gross Body Coordination

This is the ability to coordinate the *movement of the arms, legs, and torso together* in activities where the whole body is in motion.

How Gross Body Coordination Is Different From Other Abilities		
Gross Body Coordination: Involves coordination of the whole body—torso, arms, and legs.	vs.	*Speed of Limb Movement:* Involves speed of movement of arms or legs only; does not include coordination.
	vs.	*Multilimb Coordination:* Involves coordination of arms and legs only.

Requires a high degree of overall body coordination to do difficult sets of movements.

7

6 ← *Perform a skilled ballet dance.*

5

4 ← *Jump rope for five minutes without tripping or stopping.*

3

← *Get around an obstacle course with no time limit.*

Requires a small degree of overall body coordination to do simple common movements.

2

1
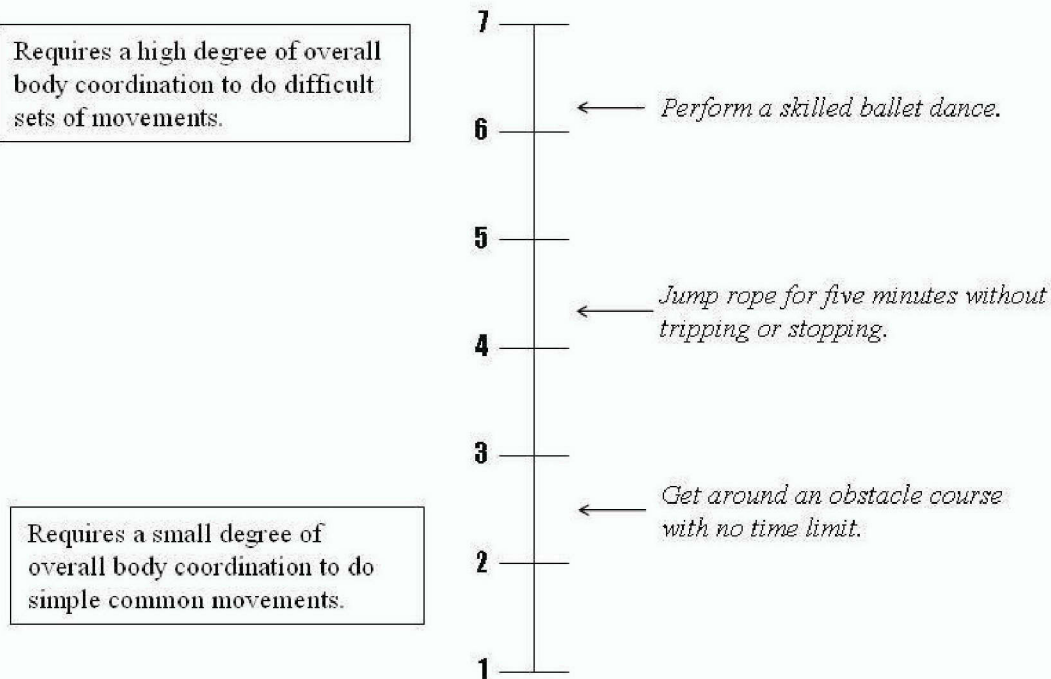
Figure 11.   Human Ability Requirement definition for Gross body coordination (courtesy of Fleishman, E. (1995), Fleishman Job Analysis Survey)

In addition to this evaluation, each of the human abilities is also represented by a seven-point scale using a rating technique that anchors both the high and low ends of the scale with some additional definitions and task examples. The use of a scaled analysis allows the application of the taxonomy to become more quantitative

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than qualitative. The scales for abilities included in F-JAS can be found in Fleishman (1995) and the abilities used in this study can also be found in Appendix-A. The scales developed or extended in reviewing users of VEs can be found in Cockayne (1998) and Darken et al (1997). An example of one of the scales developed in Cockayne and Darken (2004) is presented in Figure 11.

B.   ANALYSIS OF REAL-WORLD LOCOMOTION

Darken and Cockayne (2004) made an analysis of real world locomotion to compare to the Omni-directional Treadmill (ODT) by using the taxonomy of HARs. They needed to make some refinements due to some differences between the locomotion in ODT versus real world, since some forces applied to the user when walking on the ODT are not present in the real world. Hence, they define some "new" abilities which are actually refinements of two HARs that existed previously in F-JAS.

They refine the F-JAS HAR "*gross body coordination*" into the following three components:

1. Side-to-side coordination

2. Front-to-back coordination

3. Rotational coordination

And similarly *gross body equilibrium* into the following three components:

1. Side-to-side equilibrium

2. Front-to-back equilibrium

3. Rotational equilibrium

After completing the classification definitions, scales needed to be created. As mentioned earlier, each of

the definitions utilizes a behaviorally anchored seven-point scale. That is, the complete presence of the ability, at 7, and the complete absence of the ability, at 1, are presented in the definitions (see Figure 11).

Below is one of their first applications of classification for the reanalysis of the real-world task components using an absence/presence analysis. Table 1 shows the results of applying an absence/presence analysis to a series of human active-locomotion tasks. Although these tasks are a very small subset of locomotion tasks, they are useful for reviewing the complexity of the tasks.

REAL WORLD (Absence/Presence Analysis)	1. Multilimb Coordination	2. Rate Control	3. Response Orientation	4. Reaction Time	5. Speed of Limb Movement	6. Static Strength	7. Explosive Strength	8. Dynamic Strength	9. Trunk Strength	10. Extent Flexibility	11. Dynamic Flexibility	12. Gross Body Coordination	12(A). Side-to-Side Coordination	12(B). Front-to-Back Coordination	12(C). Rotational Coordination	13. Gross Body Equilibrium	13(A). Side-to-Side Equilibrium	13(B). Front-to-Back Equilibrium	13(C). Rotational Equilibrium	14. Stamina	15. Speed of Transport
Accelerate from Rest to Walk or Jog	●				●	●	●	●	●		●	●	■	■	■	●	■	■	■		●
Decelerate from Walk or Jog to Rest	●				●	●		●	●			●	■	■	■	●	■	■	■		●
Accelerate from Walk to Jog	●				●			●	●		●	●	■	■	■	●	■	■	■	●	●
Decelerate to Walk from Jog	●				●			●	●		●	●	■	■	■	●	■	■	■		●
Walk	●				●			●	●		●	●	■	■	■	●	■	■	■	●	●
Jog	●				●			●	●		●	●	■	■	■	●	■	■	■	●	●
Turn in Place (no forward or side movement)	●					●		●	●			●	■	■	■	●	■	■	■		
Side-Step	●					●		●	●			●	■	■	■	●	■	■	■		
Tilt Upper-Body (without Foot Movement)	●					●		●				●	■	■	■	●	■	■	■		

●   Present
■   Not Applicable

Table 1. An absence/presence analysis of real-world locomotion (Table courtesy of Darken and Cockayne, 2004)

After making the absence/presence analysis, the next step was the analysis of the same task components by scale. Below (see Table 2) are the results of the application of

the scaled analysis to the series of the same human active-locomotion tasks in the real world.

REAL WORLD (Scaled Analysis)	1. Multilimb Coordination	2. Rate Control	3. Response Orientation	4. Reaction Time	5. Speed of Limb Movement	6. Static Strength	7. Explosive Strength	8. Dynamic Strength	9. Trunk Strength	10. Extent Flexibility	11. Dynamic Flexibility	12. Gross Body Coordination	12(A). Side-to-Side Coordination	12(B). Front-to-Back Coordination	12(C). Rotational Coordination	13. Gross Body Equilibrium	13(A). Side-to-Side Equilibrium	13(B). Front-to-Back Equilibrium	13(C). Rotational Equilibrium	14. Stamina	15. Speed of Transport
Accelerate from Rest to Walk or Jog	5	1	1	1	5	2	6	6	5	1	4	5	■	■	■	5	■	■	■	2	5
Decelerate from Walk or Jog to Rest	5	1	1	1	5	2	1	5	5	1	4	4	■	■	■	4	■	■	■	1	5
Accelerate from Walk to Jog	5	1	1	1	5	1	2	6	5	1	4	5	■	■	■	5	■	■	■	2	4
Decelerate to Walk from Jog	5	1	1	1	5	1	1	5	5	1	4	4	■	■	■	4	■	■	■	1	4
Walk	5	1	1	1	4	1	1	4	3	1	3	3	■	■	■	3	■	■	■	2	2
Jog	6	1	1	1	5	1	1	4	4	1	4	4	■	■	■	4	■	■	■	4	3
Turn in Place (no forward or side movement)	4	1	1	1	1	2	1	1	3	2	1	2	■	■	■	3	■	■	■	1	1
Side-Step	5	1	1	1	1	3	1	1	3	2	1	4	■	■	■	4	■	■	■	1	1
Tilt Upper-Body (without Foot Movement)	2	1	1	1	1	3	1	1	5	1	1	3	■	■	■	3	■	■	■	1	1

1,2,3,4,5,6,or 7   Scaled Score
■   Not Applicable

Table 2.   A scaled analysis of real-world locomotion (Table courtesy of Darken and Cockayne, 2004)

The scaled analysis is especially important from the standpoint of each HAR's weighting in the task component being performed. The scaled analysis gives us the opportunity to compare the task components for the same abilities, whereas the absence/presence analysis provides a simple and quick comparison for the same task components.

C.   ANALYSIS OF OMNI-DIRECTIONAL TREADMILL (ODT)

1.   Overview of ODT

As mentioned earlier, of all the locomotion devices, treadmills are the ones that seem to offer the most attractive alternative to walking and running because of

the relatively natural feeling they provide to the user. The treadmill that is germane to this discussion is the Omni-directional Treadmill (ODT). (Darken, Cockayne and Carmein, 1997).

Although we will investigate the ODT from a human factors perspective, from an engineering perspective this device is a major breakthrough. The details of engineering and the original study can be found in Darken et al (1997).
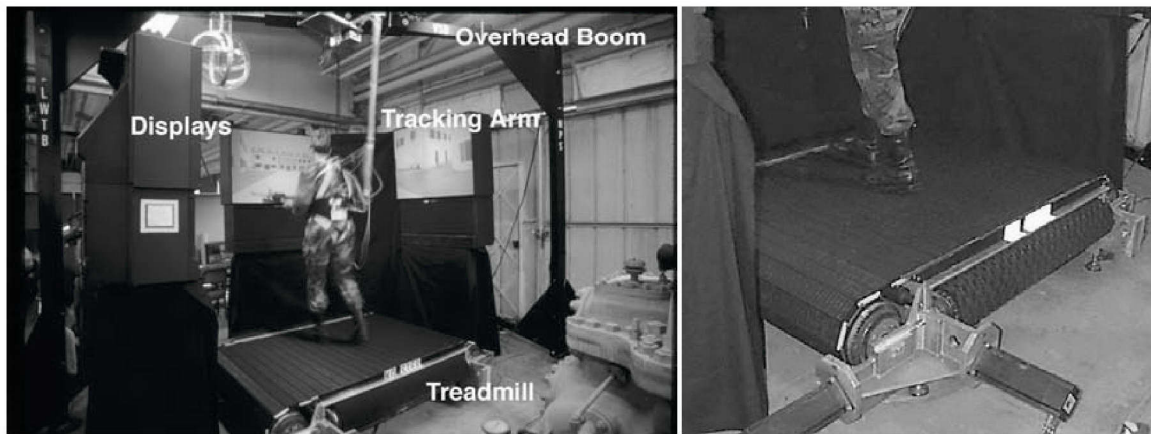
Figure 12.   The Omni-Directional Treadmill Photo Courtesy of Darken, (1997)

The ODT is a two-dimensional active treadmill that works with two orthogonal roller belts. A vector sum is calculated from the two simultaneously operating orthogonal belts and produces the motion that allows the user's movement in any direction. A mechanical tracking arm on an overhead boom (see Figure 12) measures body position and applies bias forces to center the user. Because the ODT actively applies the forces to the user, it is not a passive locomotion device.

There are two fundamental types of movement for the ODT:

- *User-initiated movement:* The user attempts to walk from the ODT's center to some position.
- *System-initiated movement:* The ODT attempts to return the user to its center.

While these movements occur, it is possible that the ODT may be late to respond to the user's rapid acceleration from rest to another state (i.e., jog, walk). Also, the user can lose his/her balance easily if the ODT cannot line up with the user's center of mass, while the ODT tries to determine the best vector of return, if the user changes his/her direction during the ODT's response time. This especially is the major problem of bipedal locomotion devices as well as ODT's. Such a device should provide precise tracking, as well as quick, calculated and actual timely response. In the case of the ODT, it is highly possible that, if the centering action is stronger than it should be, it may interfere with locomotion tasks that are needed for training.

2.   Analysis of VE Locomotion on ODT

In order to be able to make a comparison of the task components used in real world analysis versus ODT, another analysis is needed. The chart below (see Table-3) shows the absence/presence analysis of VE locomotion on the ODT of the same task components used in previous analysis. (Darken and Cockayne, 2004).

This time the analysis is realized for virtual environment rather than real world, but analyzed in the context of the user performing tasks on the ODT. You may wonder what would happen if the virtual environment was different, but please note that the study was concentrated

on motor skills rather than cognitive and behavioral skills. When you think of motor skills, especially for the task components evaluated in this study, any locomotion device or technique could have been used.

OMNI-DIRECTIONAL TREADMILL (ODT) (Absence/Presence Analysis)	1. Multilimb Coordination	2. Rate Control	3. Response Orientation	4. Reaction Time	5. Speed of Limb Movement	6. Static Strength	7. Explosive Strength	8. Dynamic Strength	9. Trunk Strength	10. Extent Flexibility	11. Dynamic Flexibility	12. Gross Body Coordination	12(A). Side-to-Side Coordination	12(B). Front-to-Back Coordination	12(C). Rotational Coordination	13. Gross Body Equilibrium	13(A). Side-to-Side Equilibrium	13(B). Front-to-Back Equilibrium	13(C). Rotational Equilibrium	14. Stamina	15. Speed of Transport
Accelerate from Rest to Walk or Jog	●	●	●	●	●	●	●	●	●		●	■	●	●		■	●	●			●
Decelerate from Walk or Jog to Rest	●	●	●	●	●	●		●	●			■	●	●		■	●	●			●
Accelerate from Walk to Jog	●	●	●	●	●			●	●	●		■	●	●		■	●	●		●	●
Decelerate to Walk from Jog	●	●	●	●	●			●	●	●		■	●	●		■	●	●			●
Walk	●	●	●	●	●			●	●	●		■	●	●		■	●	●		●	●
Jog	●	●	●	●	●			●	●	●		■	●	●		■	●	●		●	●
Turn in Place (no forward or side movement)	●	●	●	●		●		●	●			■	●	●	●	■	●	●	●		
Side-Step	●	●	●	●		●		●	●			■	●	●	●	■	●	●	●		
Tilt Upper-Body (without Foot Movement)	●	●	●	●		●		●				■	●	●		■	●	●			

● Present
■ Not Applicable

Table 3.   An absence/presence analysis of VE locomotion on the ODT (Table courtesy of Darken and Cockayne, 2004)

Just by looking at the two charts for the absence/presence analysis, you can tell that there is a significant difference in the HARs for each task component.

Darken and Cockayne also made the scaled analysis for the same task components on the ODT by using the same procedures to see the actual quantities on each HAR. Below (see Table-4) is the scaled analysis of VE locomotion on the ODT.

OMNI-DIRECTIONAL TREADMILL (ODT) (Scaled Analysis)	1. Multilimb Coordination	2. Rate Control	3. Response Orientation	4. Reaction Time	5. Speed of Limb Movement	6. Static Strength	7. Explosive Strength	8. Dynamic Strength	9. Trunk Strength	10. Extent Flexibility	11. Dynamic Flexibility	12. Gross Body Coordination	12(A). Side-to-Side Coordination	12(B). Front-to-Back Coordination	12(C). Rotational Coordination	13. Gross Body Equilibrium	13(A). Side-to-Side Equilibrium	13(B). Front-to-Back Equilibrium	13(C). Rotational Equilibrium	14. Stamina	15. Speed of Transport
Accelerate from Rest to Walk or Jog	6	4	7	7	5	3	6	7	6	1	4	■	6	6	1	■	5	6	1	4	6
Decelerate from Walk or Jog to Rest	6	4	7	7	5	3	1	6	6	1	5	■	5	7	1	■	4	7	1	1	7
Accelerate from Walk to Jog	6	4	7	7	5	1	3	7	6	1	4	■	6	5	1	■	5	5	1	4	6
Decelerate to Walk from Jog	6	4	7	7	5	1	1	6	6	1	5	■	5	6	1	■	4	6	1	1	6
Walk	6	3	3	4	4	1	1	5	4	1	3	■	5	3	1	■	4	3	1	4	4
Jog	7	2	4	5	5	1	1	5	5	1	3	■	6	3	1	■	4	3	1	6	4
Turn in Place (no forward or side movement)	5	3	3	3	1	3	1	1	4	5	1	■	5	4	6	■	4	4	6	1	1
Side-Step	6	3	4	7	1	4	1	1	4	5	1	■	7	6	5	■	7	6	5	1	1
Tilt Upper-Body (without Foot Movement)	3	2	3	6	1	4	1	1	6	1	1	■	4	7	1	■	4	7	1	1	1

1, 2,3,4,5,6,or 7 Scaled Score,
■   Not Applicable

Table 4.　　A scaled analysis of VE locomotion on the ODT (Table courtesy of Darken and Cockayne, 2004)

Although you can see that the charts are similar (or within acceptable scale range) for most of the task components for real world and ODT, there are differences. First of all, the ODT needs an extension of the abilities "*gross body coordination*" and "*gross body equilibrium*" based on orientation. VE requires a greater amount of skill than real world. Position and orientation have great importance for the tasks in VE because of the confined space, whereas there is no such requirement in real-world tasks.

Half of the abilities used in the real world to complete an active locomotion task are used similarly on the ODT. Although it can be said that ODT is usable as a locomotion device, the results of this study (Darken and

Cockayne, 2004) still need to be utilized since the other half of these real-world active locomotion abilities (the more complex ones) are not reflected accurately by the ODT.

D.   ANALYSIS OF LOCOX

1.   Overview of LocoX

One of the new locomotion interfaces in walking-in-place classification, developed by Mabini (2004) at Naval Postgraduate School, Monterey, CA, proves that it is possible to "build on the cheap."

Figure 13.   LocoX, in "walk" state. Photo courtesy of Mabini, 2004, Naval Postgraduate School, Monterey, CA

Mabini called his new "walking device" and algorithm for virtual environments LocoX. Although this thesis does not go into the details of the algorithm, a general description of LocoX is in order.

LocoX needs three magnetic sensors, one attached to each leg (a little above the knee cap) in order to recognize the state of the legs, and a third mounted atop the Head-Mounted Display (HMD) to implement the direction changes. In other words, the HMD sensor takes the place of the mouse of the computer system and provides turning in the direction in which the user is looking. The algorithm collects the information via the sensors and starts processing the data according to the phases below:

1.   Analyze leg positions: Identify the positions of each leg via the magnetic sensors and figure out the position situation that the combinations of both leg positions satisfy.

- Identify left leg's position

- Identify right leg's position (see Figure 13.a)

- Identify leg position situation satisfied by the combination of left and right leg positions (see Figure 14.a)

2.   Analyze leg velocities: Identify the velocities of the legs, which provide the primary information to determine the state of each leg.

- Identify the velocity of left leg (see Figure 15)

- Identify the velocity of right leg (see Figure 15)

- Identify leg velocity situation from one of the 17 situations using velocity matrix (see Figure 14.b)

Right Leg Position						
Left Leg Position	**0**	**1**	**2**	**3**	**4**	**5**
0	0	6	7	8	9	10
1	1	15	17	17	11	-
2	2	16	18	18	12	-
3	3	16	18	18	12	-
4	4	13	14	14	18	-
5	5	-	-	-	-	20

Right Leg Position						
Left Leg Position	**0**	**1**	**2**	**3**	**4**	**5**
0	0	6	7	8	9	10
1	1	15	17	17	11	-
2	2	16	18	18	12	-
3	3	16	18	18	12	-
4	4	13	14	14	19	-
5	5	-	-	-	-	20

a. Position situation matrix

b. Velocity situation matrix

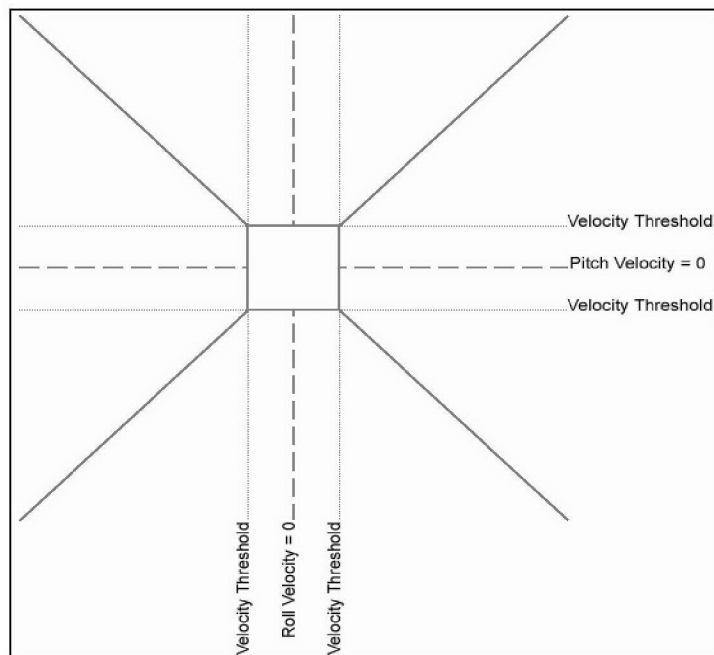Figure 14.   Analyzing the leg states in LocoX. Figures courtesy of Mabini (2004)

Figure 15.   Graph of the relationship between pitch and roll velocity. Figure courtesy of Mabini (2004)

3.   <u>Identify possible new movement type</u>: Identify new movement state using transition matrix (see Figure 16) based on old movement state, current position, and current velocity.

| Move: | Fwd Upswing | | | | | | | | | | | | | | | | |

			0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
			OO	↑O	↓O	←O	→O	O↑	O↓	O→	O←	↑↑	↑↓	↓↑	↓↓	←→	←←	→→	→←
0	O	O	0	0	0	0		0	0	0		0	0	0	0				
1	↑	O	1	1	2			1	1			1	1	2	2				
2	↓	O			3									3	3				
3	←	O				5				5						5	7	5	
4	O	↑	1	1	1			1	2			1	2	1	2				
5	O	↓							3				3		3				
6	O	→			7					7						7	7	5	
7	↑	↑																	
8	↑	↓											3						
9	↓	↑												3					
10	↓	↓																	
11	←	→				5				7									

Figure 16.   Transition matrix for walk "Upswing." Figure courtesy of Mabini (2004).

4.   <u>Check and set new movement type and speed</u>: Use conditional statements and figure out the movement speed of the user.
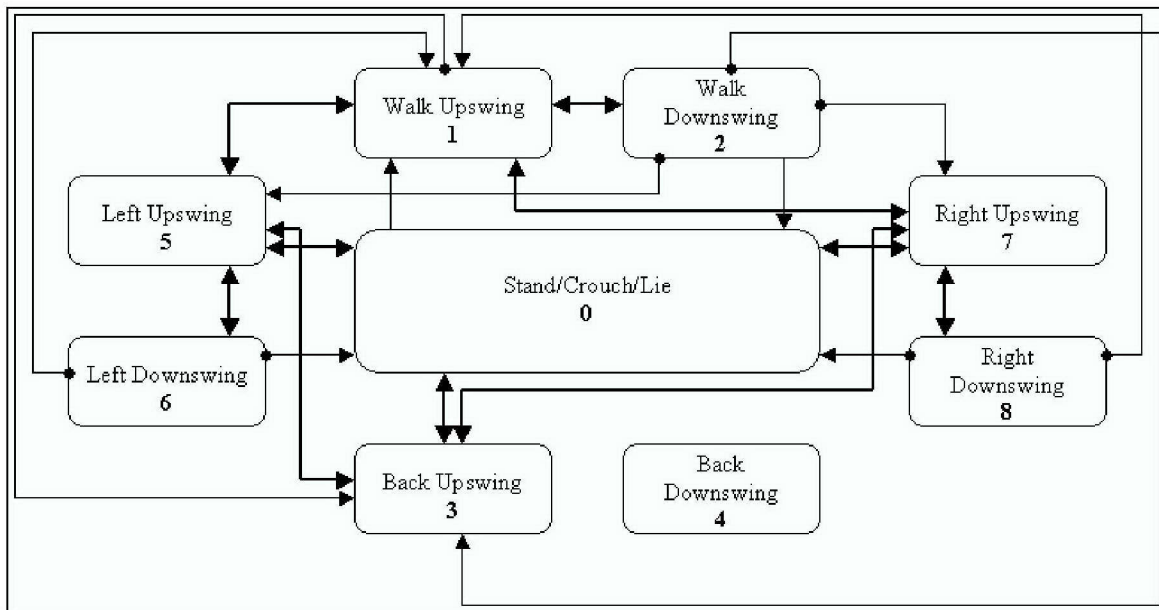

Figure 17.   Overall state transition diagram of LocoX algorithm. Figure courtesy of Mabini (2004).

More detailed information about the algorithm can be obtained from Mabini (2004).

2. Absence/Presence Analysis of VE Locomotion on LocoX

With the understanding of the algorithm, now it is time to make the analysis of VE Locomotion on LocoX using the same procedures applied to the real world and ODT.

Below (see Table-5) is the absence/presence analysis of VE locomotion on LocoX. As you may notice, the "new" abilities (i.e., side-to-side coordination, etc.) that were studied by Darken and Cockayne (2004) in the case of ODT are not applicable in the chart below. The reason for this is simply because LocoX does not need extra effort to keep balance and coordination for motion more than in the real world.

LOCOX (Absence/Presence Analysis)	1. Multilimb Coordination	2. Rate Control	3. Response Orientation	4. Reaction Time	5. Speed of Limb Movement	6. Static Strength	7. Explosive Strength	8. Dynamic Strength	9. Trunk Strength	10. Extent Flexibility	11. Dynamic Flexibility	12. Gross Body Coordination	12(A). Side-to-Side Coordination	12(B). Front-to-Back Coordination	12(C). Rotational Coordination	13. Gross Body Equilibrium	13(A). Side-to-Side Equilibrium	13(B). Front-to-Back Equilibrium	13(C). Rotational Equilibrium	14. Stamina	15. Speed of Transport
Accelerate from Rest to Walk or Jog	●				●	●	●	●	●		●	●	■	■	■	●	■	■	■		●
Decelerate from Walk or Jog to Rest	●				●	●		●	●		●	●	■	■	■	●	■	■	■		●
Accelerate from Walk to Jog	●				●		●	●	●		●	●	■	■	■	●	■	■	■	●	●
Decelerate to Walk from Jog	●				●			●	●		●	●	■	■	■	●	■	■	■	●	●
Walk	●				●			●	●		●	●	■	■	■	●	■	■	■	●	●
Jog	●				●			●	●		●	●	■	■	■	●	■	■	■	●	●
Turn in Place (no forward or side movement)	●					●		●	●		●		■	■	■	●	■	■	■		
Side-Step	●					●		●	●	●	●	●	■	■	■	●	■	■	■		
Tilt Upper-Body (without Foot Movement)	●					●			●			●	■	■	■	●	■	■	■		

●   Present
■   Not Applicable

Table 5.   An absence/presence analysis of VE locomotion on LocoX

Just by glancing at the absence/presence analysis, you can say that it is pretty similar to real-world absence/presence analysis, and that would be a correct statement. However, there are still some important differences that should be pointed out.

Explosive strength for the task component "Accelerate from Walk to Jog" is not absent in the real world, whereas it is on LocoX's chart. Although you do not need this ability in the real world, LocoX requires this extra force for you to switch from "walk" to "jog" state due to the sensors' recognition capability limitations.

Stamina is another human ability requirement that LocoX needs for the task component "Decelerate to Walk from Jog" as well as "Accelerate from Walk to Jog."

Two more abilities, dynamic strength and dynamic flexibility, are also present in the LocoX absence/presence analysis chart, whereas they are not in real-world analysis. They are required for the task component "side-step," which is one of the tasks that is hard to manage and realize in walking-in-place studies. This component shows up as quite a different one from the real world's task components, in terms of physical implementation.

The next step will be the scaled analysis of LocoX to better understand the strengths and weaknesses of its interface. Scaled analysis will provide the opportunity to compare the results more quantitatively than qualitatively to ODT and the real world. A detailed comparison of LocoX, ODT and real-world locomotion will be done to a wide extent in the last chapter of this thesis.

3. Scaled Analysis of VE Locomotion on LocoX

Below (see Table-6) is the scaled analysis of VE locomotion on LocoX. It has already been determined by the absence/presence analysis that LocoX achieves results closer to real-world locomotion than does ODT. However, the specific differences in scaling still need explanation.

LOCOX (Scaled Analysis)	1. Multilimb Coordination	2. Rate Control	3. Response Orientation	4. Reaction Time	5. Speed of Limb Movement	6. Static Strength	7. Explosive Strength	8. Dynamic Strength	9. Trunk Strength	10. Extent Flexibility	11. Dynamic Flexibility	12. Gross Body Coordination	12(A). Side-to-Side Coordination	12(B). Front-to-Back Coordination	12(C). Rotational Coordination	13. Gross Body Equilibrium	13(A). Side-to-Side Equilibrium	13(B). Front-to-Back Equilibrium	13(C). Rotational Equilibrium	14. Stamina	15. Speed of Transport
Accelerate from Rest to Walk or Jog	5				5	3	6	6	5		4	5	■	■	■	5	■	■	■	2	5
Decelerate from Walk or Jog to Rest	5				5	3		5	5		4	4	■	■	■	4	■	■	■		5
Accelerate from Walk to Jog	5				5		2	6	5		4	5	■	■	■	5	■	■	■	4	4
Decelerate to Walk from Jog	5				5			5	5		4	4	■	■	■	4	■	■	■	2	4
Walk	5					4		5	3		3	3	■	■	■	3	■	■	■	2	2
Jog	6					5		5	4		4	4	■	■	■	4	■	■	■	4	3
Turn in Place (no forward or side movement)	4					2			3	2		2	■	■	■	3	■	■	■		
Side-Step	5					3		4	3	2	4	4	■	■	■	4	■	■	■		
Tilt Upper-Body (without Foot Movement)	2					3			5			3	■	■	■	3	■	■	■		

1,2,3,4,5,6,or 7   Scaled Score,
■   Not Applicable

Table 6.   A scaled analysis of VE locomotion on LocoX

As seen in the chart above, the human requirement abilities "static strength", "dynamic strength", "dynamic flexibility", and "stamina" get different scores for some task components when compared to real-world locomotion analysis. Again, these results are much closer to the real world than is the ODT, and also much different from the ODT. Just as in absence/presence analysis, the "new" abilities are still not rated due to physical motion differences between the two locomotion interfaces.

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After completing the analysis of LocoX for VE locomotion, the next chapter will make a comparison of the ODT and LocoX to the real world from the perspective of VE locomotion and discuss the weaknesses/strengths of each versus the other.

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IV. CONCLUSIONS AND FUTURE WORK

A. DISCUSSION AND COMPARISON OF LOCOX AND ODT TO REAL WORLD FROM THE PERSPECTIVE OF LOCOMOTION IN VIRTUAL ENVIRONMENTS (VES)

So far for VE locomotion in the real world, ODT and LocoX, a task analysis has been completed in terms of HARs. The main interest was basically in human performance in real world versus performance in VEs. All efforts were made to run the evaluation by the application of HARs to task components. It should be noted, though, that this analysis cannot be considered as a replacement for traditional task analysis techniques, since HARs are not useful for evaluation of cognitive or behavioral skills.

Although there are numerous techniques and methodologies to "measure" human performance in VEs, this thesis mainly concentrated on performance of motor skills on some specific task and subtask components of locomotion (see Appendix-A). Cognitive and behavioral skills were totally held out of the evaluation and concept of this thesis, since locomotion in any VE does not, in any case, require much cognitive or behavioral skill.

Before going any farther, it should also be noted that there will always be differences in human performances for any VEs. Some people will perform better than others, either because they are familiar with these kinds of environments, they adapt themselves quicker than others, they are more talented, or some other reason. However, this will have little effect on the results of the experiment in the long run since human beings are usually able to adapt

themselves to new environments easily, so that the difference in performance will disappear or end up decreasing over time.

Darken and Cockayne (2004) concluded in their study that the ODT is usable as a locomotion device since approximately half of the abilities that a human uses in the real world to complete an active locomotion task are used similarly on the ODT. However it is also noted that the ODT does not replicate the rest of the active locomotion tasks accurately, which leads to the conclusion that it still needs to be developed and improved in order to be fully used as a VE locomotion device.

When it comes to comparing the ODT with LocoX in terms of locomotion it is still possible, even though the two are not really in the same category of locomotion (treadmills versus walking-in-place device), to make a reasonable comparison.

One major difference between the ODT and LocoX is the motion platform, with each device showing its own strengths and weaknesses. In the case of ODT: there is the powered (by human body force exertion) motion platform, although in a confined space, so that the user has the ability to perform real walking/running movement as in real-world locomotion. In the case of LocoX: a motion platform is unnecessary, but at the same time the movement that you do is not "exactly" the same as real world movement because you are "walking in place."

This need for a motion platform and all its attendant engineering disciplines make the ODT a more complex and expensive locomotion interface. LocoX, on the other hand,

proves itself to be an inexpensive device or "cheap solution" compared to the ODT. Although both devices have many good features, it is concluded from the analysis results that LocoX looks like a more competitive choice, with all the benefits for defining a new method of locomotion interface.

In addition to that, an examination of the analysis charts shows that ODT requires more or "extra" force and skill with some task components/HARs (i.e., maintaining equilibrium during transitions, coordination effort) compared to LocoX (see HARs 12.A-C and 13.A-C in Table-3 and Table-4). This necessity puts the ODT in a status of being a locomotion device which forces the user to do some extra or "unnatural" movements to satisfy the active locomotion task being studied.

The comparison of LocoX to real-world locomotion is much more promising than such a comparison involving the ODT. It is amazing to be able to provide the movement to complete active locomotion tasks with such a simple-looking algorithm. Although LocoX is still in its initial development phases, it is already demonstrating benefits that offer hope for a better locomotion device in the future.

First of all, LocoX requires movements that are already perfected in an average person's daily life. No special training whatsoever is needed to enable the user to do the experiment in an efficient way. Basically, anybody who knows how to walk and run should be able to employ the experiment. LocoX does not demand any more coordination and balance (equilibrium) than is necessary for walking/running in the real world.

Secondly, LocoX is inexpensive to build and easy to implement as a locomotion interface. It does not need "special" or "specially designed" gadgets to make it work. There are a total of three magnetic sensors that you can easily find on the open market that will give you pitch, roll and yaw values. In addition to this, a general-purpose HMD (any kind) that is standard for almost all kinds of VEs today (VEs for simulation or training purposes mentioned here) will do the job for you.

With all these thoughts, it can be said that LocoX provides quite natural movement ability to the user and is easier to implement for most task components than the ODT. However, because the user is already stationary in general, for some task components like "side-stepping" and "walking backwards" it creates somewhat of an unnatural situation. The avatar is moving along the VE, but your body is in a different motion from what you would do in the real world to walk backward or sidestep.

Another issue can be ignored. Although for most tasks LocoX uses the same muscles as in the real world, during the transitions from rest to walk/jog or vice versa, it does not need much muscle power to propel the body to satisfy the task, since the body is stationary and the other leg is not moving as it would be in the real world (e.g., forcing the other leg's thigh back/forward).

This thesis concludes that LocoX has great potential, and that the VE locomotion is realistic enough to simulate certain kinds of real-world movements from the perspective of human performance in VE. Although LocoX still requires maturation and development, it is a viable locomotion technique for VEs and future game-based simulations.

B.   FUTURE WORK: AN EFFICIENT EXPERIMENT DESIGN WITH LOCOX

Now that LocoX has been analyzed in terms of human performance in VEs by using the procedures of task analysis of motor skills with HARs, what is the next logical step for this research?

In order to better understand the strengths and weaknesses of LocoX as a locomotion interface, an efficient experiment should be designed by knowing what to measure and how to measure it. This section will focus on giving the general idea for a future experiment to analyze LocoX from the perspective of effectiveness, potential, and usability.
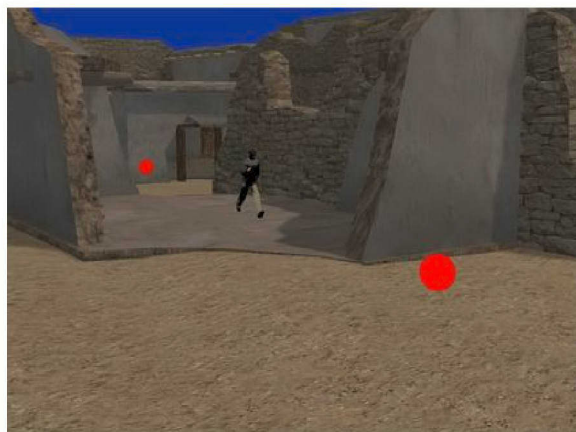
1.   Instrument List to Use

There are many different equipments/instruments on the market today that allow for the building of a VE experiment, but due to the specific needs of LocoX, here is a possible/generic list of instruments that can be used:

- A virtual environment in which the scenario will be implemented (i.e., America's Army, Unreal Tournament, custom-built VE with a game engine such as Delta3D, etc.)

a. Screen shot from a   b. Screen shot from a virtual
   virtual town   town with waypoints
Figure 18.   Screen shots from a possible virtual environment
          (built using Delta3D open-source game engine)

- A computer with monitor to operate the experiment. Monitor can be replaced with a big screen projector or a system like CAVE depending on the needs of the investigator, since the user will not need the big screen during the experiment.

Figure 19.   CAVE environment example. Photo courtesy of MOVES Institute, Naval Postgraduate School, Monterey, CA

- Three magnetic sensors (i.e., Intersense IS-300 Pro Tracker System, http://www.isense.com/. See Figure 20.b below). Two of these sensors will be attached to the user's legs, just above the knee caps.
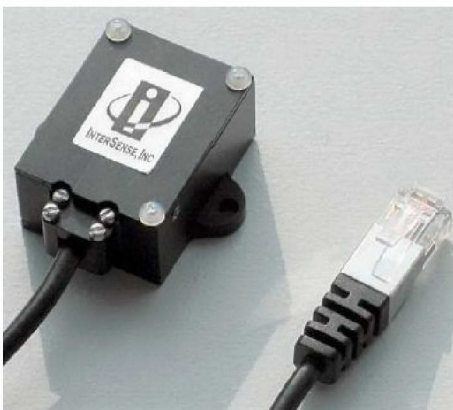
a. InertiaCube3   b. InterSense IS-300 Pro

Figure 20.   Magnetic sensors that can be used in experiment. Photos courtesy of InterSense, http://www.isense.com.

- Head-mounted display (HMD) with a sensor mounted on the top of it (to determine the direction user is looking by tracking head movement).

Figure 21.   HMD with a magnetic sensor mounted on top of it

- A system to record/track the body movements of the user, both in the confined lab space and in VE, to analyze later.

Although the above list will satisfy the requirements of the experiment that will be mentioned here, any component of the list can be replaced with an alternative or any additional component can be added due to the needs. It should be kept in mind that the primary purpose of the experiment would be to get the maximum usable results in order to analyze the device's efficiency as a locomotion interface to VEs.

2.   Implementation Method

The time to complete the experiment should be between 30-45 minutes in total (including practice time in the environment, this period may extend to an hour) considering the structure of the experiment and the possible after-effects of the head-mounted display. Although it is uncommon, some people may occasionally have a slight increase in salivation, stomach awareness, or headache upon

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completion of such an experiment due to wearing a head-mounted display (HMD) for a prolonged period of time. The users should be briefed before and after the experiment and advised to avoid operating any vehicle for at least one hour to allow their vision to readjust to normal light and head movement.

There will be four main task components/motions to test and analyze (due to the limitations of the algorithm of LocoX):

Walking (forward/backward)

Turning right/left

Side-stepping

Running

Jumping and crawling may be added to these tasks with the future revisions of LocoX.

The primary measurement criteria will be the accuracy of the moves, to determine how realistically LocoX represents the user's moves in VE. There may be additional data to collect and analyze that is not directly related to LocoX's algorithm but supports the results of the experiment and conclusion. Examples of such data might be the time to accomplish the mission and the ease of use of the equipment.

In order to get the measurements right and also notify the user of the change of the move effectively and on time, it will be useful to force the user to follow some straight/curved lines in VE (i.e., 50 feet of blue line for walking, 10 feet of red line for side-stepping, etc).

As a side measurement, a task such as navigation or finding and picking up hidden stuff in VE may be assigned

so that the user will concentrate on the task rather than trying to do the motions correctly. Otherwise, it is possible to get some interesting or unnatural results due to the user's paying excessive attention to the main task components or exaggerated motions.

After completion of the experiment, LocoX may be easily analyzed from the perspective of locomotion according to the records of the users. In addition to this, a post-experiment questionnaire that will be applied to the users with salient questions about general comfort of the device, ease of usage, naturalness of the motions in VE, etc. will probably aid in a final conclusion.

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APPENDIX A.   LIST OF TASK COMPONENTS USED IN ANALYSIS

A.   PRIMARY FACTORS

These are the four primary factors to describe active locomotion tasks on the Omni-Directional Treadmill (ODT) (Darken, Cockayne, 1997);

1.   Relative velocity: Rest, walk, or jog. This defines the approximate relative velocity of the user when not accelerating or decelerating. Running is not possible on the ODT, nor is crawling or kneeling.

2.   Transition: Accelerate or decelerate. As will become evident in the scaled analysis, the rate of acceleration or deceleration is a critical factor. It may or may not imply a change in gait.

3.   Movement direction: Forward or backward. Sidestepping is considered a maneuvering task component.

4.   Direction change: Straight or turn. This describes whether a direction change takes place during a transition or at constant velocity.

B.   ACTIVE LOCOMOTION TASK COMPONENTS

These are the active task components that we investigate for the locomotion in real world, ODT and LocoX.

- *Walk*: At least one foot is touching the ground at all times

- *Jog*: Neither foot may be touching the ground at any time

- *Acceleration from rest to a walk or jog*: Change of state

- *Deceleration to rest from a walk or jog*: Change of state

- *Acceleration from walk to jog*: Change of gait

- *Deceleration to walk from jog*: Change of gait

- *Turning in place (no forward or lateral movement)*: Maneuvering action

- *Sidestepping (purely lateral movement)*: Maneuvering action

- *Tilting upper body without foot movement*: Maneuvering action.

APPENDIX B. HUMAN ABILITY REQUIREMENTS (HARS) REQUIRED FOR ACTIVE LOCOMOTION

Below is a list of human ability requirements (HARs) definitions required for active locomotion (used in this research) (Fleishman, 1995).

1. *Multilimb coordination*. This is the ability to coordinate the movements of two or more limbs (e.g., two legs, two hands, one leg and one hand). The ability does not apply to tasks in which trunk movements must be integrated with limb movements. It is most common to tasks where the body is at rest (e.g., seated or standing) while two or more limbs are in motion.

2. *Rate control*. This is the ability to make timed, anticipatory motor adjustments relative to changes in the speed and/or direction of a continuously moving object. The purpose of the motor adjustments is to intercept or follow a continuously moving stimulus whose speed and/or direction vary in an unpredictable fashion. This ability does not extend to situations in which both the speed and direction of the object are perfectly predictable.

3. *Response orientation*. This is the ability to select and initiate the appropriate response relative to a given stimulus in a situation where two or more stimuli are possible and where the appropriate response is selected from two or more alternatives. The ability is concerned with the speed with which the appropriate response can be initiated and does not extend to the speed with which the response is carried out. This ability is independent of the mode of stimulus presentation (auditory or visual) and also of the type of response required.

4. *Reaction time*. This ability involves the speed with which a single motor response can be initiated after the onset of a single stimulus. It does not include the speed with which the response or movement is carried out. This ability is independent of the mode of stimulus presentation (auditory or visual) and also of the type of motor response required.

5. *Speed of limb movement*. This ability involves the speed with which discrete movements of the arms or legs can be made. The ability deals with the speed with which the movement can be carried out after it has been initiated; it is not concerned with the speed of initiation of the movement. In addition, the precision, accuracy, and coordination of the movement are not considered under this ability.

6. *Static strength*. This is ability to use continuous muscle force to lift, push, pull, or carry objects. This ability can involve the hands, arms, back, shoulders, or legs. It is the maximum force that one can exert for a brief period of time.

7. *Explosive strength*. This is ability to use short bursts of muscle force to propel oneself, as in jumping or sprinting, or to throw objects. It requires gathering energy for bursts of muscular effort.

8. *Dynamic strength*. This is ability of the muscles to exert force repeatedly or continuously over time. The ability involves the degree to which the muscles do not "give out," or fatigue. The ability is involved in supporting, holding up, or moving objects or the body's own weight repeatedly over time.

9. *Trunk strength*. This ability involves the degree to which one's stomach and lower back muscles can support part of the body or the position of the legs, repeatedly or continuously over time. The ability involves the degree to which these trunk muscles do not "give out," or fatigue when they are put under repeated or continuous strain.

10. *Extent flexibility*. This is the ability to extend, flex, or stretch muscle groups. It concerns the degree of flexibility of muscle groups but does not include repeated or speed flexing.

11. *Dynamic flexibility*. This is the ability to make repeated trunk and/or limb flexing movements where both speed and flexibility of movement are required. It includes the ability of these muscles to recover from the strain and distortion of repeated flexing.

12. *Gross body coordination*. This is the ability to coordinate movements of the trunk and limbs. This ability is most commonly found in situations where the entire body is in motion or being propelled.

12(A). *Side-to-side coordination*. This is the ability to coordinate movements of the trunk and limbs along the axis passing through both of the user's shoulders. This ability is most commonly found in situations where the entire body is in motion or being propelled across the plane of the user's chest.

12(B). *Front-to-back coordination*. This is the ability to coordinate movements of the trunk and limbs along the axis passing through the user's chest. This ability is most

commonly found in situations where the entire body is in motion or being propelled in the plane perpendicular to the user's chest.

12(C). *Rotational coordination*. This is the ability to coordinate movements of the trunk and limbs in rotation about the axis passing through the user's head and the ground. This ability is most commonly found in situations where the entire body is in motion or being propelled around the axis perpendicular to the ground.

13. *Gross body equilibrium*. This is the ability to maintain the body in an upright position or to regain body balance, especially in situations where equilibrium is threatened or temporarily lost. This ability involves only body balance; it does not extend to the balancing of objects.

13(A). *Side-to-side equilibrium*. This is the ability to maintain the body in an upright position or to regain body balance, especially in situations where equilibrium is threatened or temporarily lost. This ability involves only body balance across the plane of the user's chest; it does not extend to the balancing of objects.

13(B). *Front-to-back equilibrium*. This is the ability to maintain the body in an upright position or to regain body balance, especially in situations where equilibrium is threatened or temporarily lost. This ability involves only body balance in the plane perpendicular to the user's chest; it does not extend to the balancing of objects.

13(C). *Rotational equilibrium*. This is the ability to maintain the body in an upright position or to regain body balance, especially in situations where equilibrium is

threatened or temporarily lost. This ability involves only body balance around the axis perpendicular to the ground; it does not extend to the balancing of objects.

14. *Stamina*. This ability involves the capacity to maintain physical activity over prolonged periods of time. It is concerned with resistance of the cardiovascular system (heart and blood vessels) to breakdown.

15. *Speed of transport*. This ability involves the speed with which the human propels the whole body through space. The ability deals with the speed with which the movement can be carried out after it has been initiated; it is not concerned with the speed of initiation of the movement. In addition, the precision, accuracy, and coordination of the movement are not considered under this ability.

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